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VIBRATION SENSOR AND PROCESS FOR MONITORING THE STATE OF ROTATING COMPONENTS AND BEARINGS

The invention relates to a vibration sensor for monitoring the state of rotating components or bearings, with a sensor element, with evaluation electronics and with at least one interface. In addition the invention also relates to a process for monitoring the state of rotating components or bearings with a vibration sensor which has a sensor element and evaluation electronics.

In mechanical engineering and plant engineering there are a host of machines and systems which each have rotating components, generally a shaft. The shaft is supported here via a bearing, especially a roller bearing, in the stationary housing of the machine or equipment, depending on the embodiment the inside ring or the outside ring of the bearing being movably arranged, while then accordingly the inside ring or the outside ring is supported to be stationary. Problem-free serviceability of the bearing as the force-transmitting component in motion is decisive for the serviceability of the machine or system. Due to high dynamic and static loads in operation and as a result of structural limitations, the bearing often constitutes the "Achilles heel" of the machine or system. Thus, bearing defects are by far the most frequent cause of failure for electrical drives.

For this reason there are a host of various sensors and methods for monitoring the state and for detection of bearing damage. In addition to measuring the temperature of the bearing and analyzing the bearing lubricants, especially of the bearing oil, mainly vibration-diagnostic methods are used to assess the state of the bearing. Using an acceleration sensor the solid-borne noise signal of the bearing which is to be monitored on the machine surface is detected and analyzed. In doing so however simple characteristic values of the vibration signal such as the effective value, the peak value or the quantitative average do not allow reliable conclusions about the state of the monitored bearing. In particular, for early detection of damage these characteristic values are completely unsuited. This is also due especially to complex operating conditions and to the host of bearings which can be used and which are used with their different dimensions and characteristic values.

Reliable early diagnoses of bearing damage or unbalanced masses of rotating

components is therefore only possible with comprehensive evaluation of the high frequency signals delivered by the vibration sensor in the range up to a few kilohertz. The evaluation of these high frequency signals generally takes place using spectral signal analysis. In this way it is not only possible to draw a conclusion regarding whether a bearing is intact or damaged, but a conclusion can also be drawn about the type of damage. Likewise a conclusion can be drawn about the expected remaining service life of the bearing. Although it is thus possible by measurement engineering to detect varied damage early, vibration sensors for monitoring the state of rotating components or bearings are used only rarely in practice.

The prior art in industrial monitoring of bearings is limited on the one hand to intermittent measurement with hand measuring instruments, on the other hand to the use of relatively expensive central measurement systems which as a result of high procurement costs are feasible only for monitoring of high-value machines such as turbines or large gear trains. Intermittent measurement with hand measuring instruments has the disadvantage that continuous checking of the state of the bearing does not take place, so that reliable early diagnosis of damage is not possible. Moreover, as a result of the different operating conditions it is only possible with difficulty to draw a reliable conclusion about the state of the bearing from the different measured values. To do this the corresponding expert know-how is necessary; this is associated with high personnel expenditure and this also with high costs.

In the implementation of a central measurement system, as a result of the large number of data to be evaluated, on the one hand the cabling of the individual vibration sensors to the central data processing systems is complex, on the other hand due to the real time capacity which is often required very high demands are imposed on the central data processing system, the central data processing system for reasons of safety in addition often having to be made redundant. But even in the use of a correspondingly powerful and high-speed data processing system, due to the large number of data to be evaluated the number of sensors which can be connected to the data processing system is very limited, if the individual sensors are to be evaluated in real time and not only in a multiplex process. Because the individual sensors must be connected to the central data processing system via separate lines, such a central measurement system has an expansion capacity which is made

very limited or has none at all. Thus, planning of a central measurement system requires thorough preparation, machines and sensors which may have to be added at a later time having to be taken into account at the same time in planning.

Therefore the object of this invention is to embody and develop the initially described vibration sensor and the initially described process such that reliable monitoring of the state of rotating components and bearings can be done easily and thus economically, and in addition the vibration sensor is to be operated in a manner as simple as possible.

This object is achieved in the initially described vibration sensor by the evaluation electronics having an analog/digital converter and a signal conditioning means and in the signal conditioning means a plurality of signals which have been acquired by the sensor element being converted into a state value using signal analysis and a diagnosis algorithm. By the integration and execution of the signal conditioning means thus bearing diagnosis is integrated into the vibration sensor. By converting the plurality of measured signals using signal analysis and the diagnosis algorithm in a simple state value expensive expert know-how for reliable bearing diagnosis and for detection of bearing damage can be abandoned.

Basically the sensor element on the one hand and the evaluation electronics and the interface on the other can be arranged in space separately from one another. This is especially the case when on the machine which is to be monitored there is only very little space for mounting of the vibration sensor so that then only the sensor element is mounted on the machine, while the evaluation electronics is located spatially separated from it. The sensor element and the evaluation electronics are then connected to one another via an electrical line. But preferably the sensor element and the evaluation electronics are located in a common housing so that the vibration sensor is a so-called compact device.

According to one preferred embodiment the vibration sensor as claimed in the invention has a display means with a display and with at least one control element for parameter input and/or for setting the boundary values and/or for choosing the operating mode of the vibration sensor. Thus simple indication of the determined state value is possible on site using the display so that the state of the monitored component or of the monitored bearing can be easily read out at any time. Using the control elements, on the one hand, the vibration sensor can be switched into the desired operating mode, on the other hand matching

to the operating conditions present at the time by input of certain parameters or boundary values is possible. Preferably the display has a color display with the color values green, yellow and red so that in this way the respective state of the bearing and the deterioration of the bearing state can be indicated easily and still distinctly.

In order to preclude manipulation of the parameters which have been input using the control elements by an individual who is not authorized to do so, the control elements are made such that they can be locked or blocked mechanically and/or electronically. Mechanical locking can be made for example such that only after inserting a special key into a corresponding lock on the housing are the control elements activated. Alternatively the control elements can be activated or deactivated electronically by means of a PC, so that manipulation security can also thus be ensured.

According to another preferred embodiment of the vibration sensor as claimed in the invention the interface has at least one switching output, a parameterization input and a current and voltage supply input. The interface can moreover also have a signal input for an external signal and a current or voltage supply output for an external sensor. Based on the parameterization input especially simple PC-supported parameterization via a standard interface, for example a RS-232 interface, is possible.

In this way user-friendly input and setting of all parameters relevant to monitoring, such as bearing data, rpm, boundary values and operating function of the outputs, are possible on a PC, and especially the bearing data can be stored in the corresponding databases in the PC so that the user need input only the corresponding type designation or characteristic values of the bearing and then all relevant data are transferred from the PC via the interface as the parameter set to the vibration sensor. Likewise a bearing database can also be filed in a memory which is integrated into the vibration sensor so that the operator in the parameter input from the database can easily select the correct characteristic values by input of the bearing size and of the manufacturer.

By the execution of a signal input for an external signal the vibration sensor can continuously carry out state monitoring even when the rpm change. The information which is routed to the signal input about the current rpm can arrive either via an analog current signal (4 to 20 mA) from the motor control of the rotating component or from an external sensor, for

example a proximity switch or pulse generator. Because there is also a current or voltage supply output, the current and voltage supply of an external sensor can take place via the vibration sensor or the current and voltage supply connection. In this way a further reduction of the cabling cost is possible since the external sensor need be connected only to the spatially adjacent vibration sensor and not to a spatially remote supply unit.

Advantageously the interface has two switching outputs which each can be switched as a break contact or a make contact, the one switching output triggering a pre-alarm and the other switching output triggering the main alarm. Thus, in addition to the display, indication of the respective state of the rotating component or the bearing is also possible at a remote site, for example, a central monitoring site, via the switching outputs. The switching output which triggers the main alarm and which indicates damage which adversely affects the serviceability of the rotating component and/or of the bearing can be connected to an emergency stop switch of the machine and an optical and/or acoustic signal means.

The evaluation electronics which is formed for example by a microprocessor according to another preferred embodiment has self-learning logic. Using this self-learning logic in which defined and preset damage patterns are compared continuously with the current measured values, self-learning damage pattern recognition is possible.

According to another embodiment of the vibration sensor as claimed in the invention, the vibration sensor is designed for state monitoring of several rotating components or bearings, for each monitored component or for each bearing the acquired signals being converted using signal analysis and a diagnosis algorithm into a state value and the state value of the component or of the bearing with the greatest degree of damage, i.e. the poorest or most critical state value, being at the switching output of the vibration sensor. The evaluation electronics thus undertakes comparison of the state values of the individual monitored components and bearings, only the "most critical" state value being sent to the switching output at one time. In this way, with the single vibration sensor as claimed in the invention monitoring of several rotating components or bearings is possible, and expensive expert know-how for evaluation and diagnosis of the individual measured values can be abandoned since the relevant state is easily detected by the vibration sensor and is clearly displayed.

So that the vibrations of the bearing which is to be monitored, which vibrations have been detected by the sensor element, are not superimposed or adversely affected by the natural vibrations of the housing, the sensor element is advantageously located on a circuit board which has at least one rigid segment and at least one flexible segment. The sensor element is mounted with low attenuation in the housing in the vicinity of the mounting site of the vibration sensor. In this way, transmission of the solid-borne sound of the bearing which is to be monitored to the sensor element, which transmission is as optimum as possible, is ensured.

According to a last advantageous embodiment of the vibration sensor as claimed in the invention which will be briefly described here, the sensor element is a biaxial acceleration sensor which is advantageously located at an angle of 45 degrees to the surface normal on the circuit board. These acceleration sensors at present can be produced relatively favorably, but they have a relatively high noise portion in the acceleration signal. In the aforementioned advantageous embodiment in which the acceleration signal is located turned by 45 degrees on the circuit board, the noise portion can be reduced by the output signals of the two channels (axes) of the acceleration sensor being added. In this way, on the one hand however the amplitude of the useful signal corresponds to one uniaxial sensor, on the other hand however the amplitude of the noise portion is greatly reduced since from each channel only half the noise amplitude is routed to the analog/digital converter.

In the initially described process the object of the invention is achieved in that the signals acquired by the sensor element are converted into a state value using signal analysis and a diagnosis algorithm. In doing so the sensor element continuously or quasi-continuously acquires the signals so that there is continuous monitoring of the state of the system. Signal analysis takes place advantageously both in the time domain and also in the frequency domain, by which high signal resolution can be achieved so that even under difficult operating conditions reliable state monitoring can be accomplished.

In order to be able to process the host of measured signals with high precision, but still with computer cost as small as possible, there are various possibilities of signal analysis which are used alternatively or preferably combined. Signal analysis take place first of all based on a Fourier transform (FT), a fast Fourier transform (FFT) or an envelope curve fast

Fourier transform (HFFT). The known mathematical transform possibilities are modified such that very fine spectral resolution is achieved. To do this for example a so-called zoom FFT can be used as frequency analysis by which the accuracy in frequency resolution (discrimination) is increased. Moreover, preferably intelligent dynamic scaling of the respective frequency band is implemented, by which the accuracy is increased for the amplitudes.

To prevent anti-aliasing problems, the frequency range is limited using an analog filter. Preferably the boundary values of the filter can be variably set depending on the operating conditions or can be automatically matched themselves to altered operating conditions. Then analog/digital conversion takes place for example using a sigma-delta converter so that the measured analog signals can be digitally processed in the evaluation electronics.

In order to be able to evaluate the large number of measured values with reasonable effort and in real time, dynamic quantitative averages and peak values are computed in the time domain. Parallel thereto in the frequency domain the values which are supplied to signal analysis are manipulated, i.e. individual signals are weighted and/or filtered and/or windowed and/or modulated.

Using a diagnosis algorithm, individual signals are combined into characteristic values which are compared to boundary values, individual signals being weighted according to their relevance. Computation of the individual characteristic values is done depending on the stored and/or computed parameter data so that the process as claimed in the invention can be used for different components and different bearings. The individual characteristic values are then likewise combined with consideration of different weighting and with consideration of the operating state into a state value which is output by the vibration sensor.

If damage occurs on one of the components of the bearing, i.e. on the inside ring, on the outside ring or on the roller body, this is measured by the vibration sensor by an altered solid-borne noise signal. Different "damage frequencies" are assigned to the individual components. In systems in which a host of broadband vibrations occur, there is the danger that the vibration sensor detects the "damage frequency" of a component of the bearing which originates from the superposition of a vibration from the system and not from a fault of the

component of the bearing which has actually occurred. Therefore, advantageously in the process as claimed in the invention, to produce a reliable damage conclusion the signals which have been measured for the individual components of the bearing are combined into a characteristic value. If the characteristic values are not computed in the vibration sensor in isolation for the individual components of the bearings, but, as stated above, are determined by the corresponding averaging or weighting of the signals of at least two components of the bearing, the danger of occurrence of a false alarm by the superposition of external vibrations is reduced.

Using the above described diagnosis algorithm, thus the host of signals which have been measured altogether is combined into some characteristic values, the individual characteristic values representing the different types of damage of the rotating component or of the bearing. In the computational combination of the individual signals into the characteristic values the varied relevance of individual signals under different operating conditions and for different parameter data which have been input beforehand can be considered.

According to another advantageous embodiment of the process as claimed in the invention, the characteristic values and/or the state value is subjected to plausibility checking so that measurement errors are recognized and a faulty state value is not output. In the plausibility checking of the characteristic values and/or of the state value it is taken into account that the damage which occurs on the rotating component or on the bearing does not generally occur spontaneously, but arises and grows over the course of time so that by comparing the characteristic values and/or the state value at a past time to the current characteristic value and/or the current state value a measurement error can be ascertained.

According to one preferred embodiment both of the vibration sensor as claimed in the invention and also of the process as claimed in the invention, the vibration sensor has different operating modes. In the so-called teach-in mode the boundary values are automatically computed depending on the parameterization data and the current operating conditions by the evaluation electronics. In such an automatic self-learning process thus at the start of monitoring of the state the current measurement values are stored as the reference values so that when the reference values diverge from the measured values which are

theoretically expected based on parameter data, automatic matching of the selected boundary values can take place.

According to one preferred configuration the teach-in mode as an additional operating mode has teaching of the response characteristic between the rotating component or the bearing and the vibration sensor. The response characteristic is dependent on the respective conditions of use of the vibration sensor, especially on the mass and geometry of the rotating component and on the damping behavior of the materials used. In order to determine the actual response characteristic, advantageously at the start of monitoring of the state at least one defined pulse in the three-dimensional vicinity of the rotating component is fed into the machine and a response characteristic is determined from the signal which has been measured by the vibration sensor based on the pulse. The pulse can be produced either simply by a corresponding tool, for example an impact punch, or by a mobile apparatus. If instead of a simple tool a mobile apparatus is used, different pulses with different frequencies and amplitudes can be produced so that then the response characteristic can be determined over a larger frequency range.

It was stated above that with the vibration sensor as claimed in the invention according to one preferred embodiment state monitoring is also possible at different rpm. In this case the process as claimed in the invention is further developed such that the boundary values which have been computed or input beforehand are automatically adapted to the respective rpm. The teach-in mode need therefore be carried out only for a typical operating rpm; at a different rpm then the corresponding boundary values are then automatically computed by the evaluation electronics so that the teach-in mode need not be carried out for each possible operating rpm.

According to a last advantageous embodiment of the process as claimed in the invention which will be briefly described here, the determined state values are continuously stored, and based on the previously determined state values a computation of the expected time interval (remaining service life) until occurrence of damage which adversely affects the serviceability of the rotating component and/or of the bearing is determined. In this way not only is the current state of the monitored component or the monitored bearing displayed to the user, but the latter also acquires information about how long the monitored machine or

equipment can continue to be operated and when repair or replacement of the bearing must be done before damage or failure of the machine or equipment can be expected.

In particular, there is now a host of possibilities for embodying and developing the vibration sensor as claimed in the invention and the process as claimed in the invention. In this regard reference is made on the one hand to the claims which are subordinate to claim 1 and claim 18, on the other hand to the description of one preferred embodiment in conjunction with the drawings.

Figure 1 shows a schematic block diagram of a vibration sensor as claimed in the invention,

Figure 2 shows a concrete embodiment of the vibration sensor as claimed in the invention, in a front view,

Figure 3 shows a second concrete embodiment of the vibration sensor as claimed in the invention, in a side view and

Figure 4 shows an embodiment of the vibration sensor as claimed in the invention, in a section.

The figures show a vibration sensor 1 with a plastic or aluminum housing 2, with a sensor element 3 which is located in the housing 2 and which is shown only schematically in Figure 1, with likewise only schematically shown evaluation electronics 4 and with two interfaces 5, 6. The evaluation electronics 4 which is shown only schematically in Figure 1 has an analog/digital converter 7 which is connected to the sensor element 3 and a signal conditioning means 8 which is connected to the analog/ digital converter 7. The signal conditioning means 8 is generally implemented by a microprocessor which can form the evaluation electronics 4 altogether so that the analog/digital converter 7 is integrated in the microprocessor.

As can be recognized from Figure 2, the vibration sensor 1 has a display means 9 with a display 10 and three control elements 11, 12, 13. The control elements 11 and 12 are used on the one hand for setting boundary values; when these boundary values are reached a pre-alarm or main alarm is triggered by the vibration sensor 1. Moreover the operating mode and/or the display mode of the vibration sensor 1 can also be selected via the controls 11, 12. The control element 13 is used to start the teach-in mode in which the vibration sensor 1 is

automatically matched to the current operating conditions after completed parameterization in the installed state.

The display 10 according to the preferred embodiment has a color display, there being several green LEDs 14, several yellow LEDs 15, and several red LEDs 16. Via the first green LED 14 proper power supply of the vibration sensor 1 is displayed, while via the second green LED 14 the operating status of the vibration sensor can be displayed (parameterization, teach-in mode, monitoring mode). Using several yellow LEDs 15 the progress of the degree of damage of the monitored component or of the monitored bearing is indicated. Depending on the setting of the boundary values a pre-alarm is output parallel to the display via a yellow LED 15. Via the red LEDs 16 finally the damage of a component or of a bearing is displayed, with the illustrated vibration sensor 1 several bearings being able to be monitored at the same time, so that the individual red LEDs 16 are assigned to the individual bearings. Parallel to lighting of a red LED 16 the main alarm is output via the interface 5.

The interfaces 5, 6 which are schematically shown in Figure 1 in the specific embodiments of the vibration sensor 1 as claimed in the invention which are shown in Figures 2 and 3 are implemented by two plug connectors 17, 18, the two interfaces 5, 6 being made as RS 232 interfaces and the two plugs 17, 18 being made as M12 and M8 plug connectors. The plug 17 has a current and voltage supply connection, two switching outputs which can be programmed as break contacts or make contacts for the pre-alarm and the main alarm, and a signal input for an external signal which corresponds to the current rpm. The plug 18 likewise has a signal input for an external signal and moreover a current and voltage supply output via which an external sensor can be supplied. Moreover the vibration sensor 1 can also be connected via the plug 17 to a computer, especially a PC, the parameterization data then being transmitted as data packets from the PC. This data transfer can moreover take place besides via a RS-232 interface for example also via a RS 485 interface.

The adjustable parameters can be especially characteristic data of the bearings, operating data of the system or machine, and boundary values. The characteristic data of the bearings are especially the number of roller bodies, i.e. of balls, grooves or barrel roller bodies, the roller body diameter and the diameter of the inside ring of the bearing and of the outside ring of the bearing. These individual parameters can be input either manually on the

PC or they are preferably made available automatically from a database simply by specification of the bearing manufacturer and the bearing identification number. Moreover, the operating rpm or at variable rpm the possible rpm range, the manner in which the rpm are made available, the boundary values and the setting of the switching outputs (break contact or make contact) can also be set in the parameterization mode.

Figure 1 shows that the evaluation electronics 4 has two memories 19, 20, in the one memory 19 the set parameter values and boundary values as well as the current operating data being stored, while the other memory 20 acts as a history memory in which the state values which have been determined by the vibration sensor 1 are continuously stored.

Figures 2 to 4 moreover show that the vibration sensor 1 as claimed in the invention is made roughly cuboidal, its preferably having a very compact design, for example having an edge length of less than five centimeters, on the front side of the housing 2 a beveled top side 21 being formed, in which the display means 9 is integrated. In this way, both the operability of the control elements 11, 12, 13 and also the readability of the display 10 are facilitated or enhanced. The mounting of the illustrated vibration sensor 1 on a machine or system which is to be monitored takes place via a screw connection 22, but can also be implemented by cementing. Finally, it is apparent from Figure 2 that above the display 10 there are labelling fields 23 which on the one hand symbolize the progress of the damage state for the display via the yellow LEDs 15, on the other hand which enable assignment of the individual red LED 16 to the individual bearings.

Figure 4 shows that the sensor element 3 is located on a circuit board which consists of three rigid segments 24 and three flexible segments 25. This circuit board construction is also often called a rigid-flexible circuit board. The sensor element 3 is attached by means of a low-attenuation cement 26 in the vicinity of the mounting site of the vibration sensor 1, i.e. in the vicinity of the screw connection 22, within the housing 2. Because the sensor element 3 is separated from the remaining circuit board construction by the flexible segment 25 which is made as a conductor film, the sensor element 3 is decoupled in terms of vibration technology from the remainder of the circuit board construction. Thus superpositions of natural vibrations of the vibration sensor 1 onto the sensor element 3 are for the most part avoided. Finally, Figure 4 shows that the rigid-flexible circuit board construction is screwed securely

using spacers 27 and disk springs 28 within the housing 2.